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GIS spatial modelling for seismic risk assessment based on exposure, resilience, and capacity indicators to seismic hazard: a case study of Pahang, Malaysia

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ABSTRACT

Various techniques and frameworks for an evaluation of seismic vulnerability have been developed and established in previous studies. However, some techniques demand a significant amount of empirical data currently not readily available in developing countries. Therefore, this study proposes a new seismic risk evaluation method at the local district level. A holistic model was constructed for the purpose of assessing potential seismic vulnerability based on appropriate indices and their relative contribution towards vulnerability and coping capacity. It allowed the estimation of vulnerability in terms of exposure, resilience, and capacity factors. Then, utilization of Geographical Information System (GIS) tools resulted in the generation of a total vulnerability map via integration of the study variables to highlight the socio-economic and physical characteristics of vulnerability for the districts in Pahang, Malaysia. Subsequently, a seismic risk map of the study area was derived by overlying the derived map with the seismic hazard map. Consequently, the study revealed the highest levels of seismic risk were concentrated in the central-west of the Pahang region, namely the Bentong district. In contrast, the least vulnerable areas encompassed the Pekan and Jerantut areas, which were located in the eastern region. In brief, the study findings would serve as the foundation towards reducing the country's vulnerability to disasters.

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vulnerability index; seismic
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1. Introduction

It is projected that by the year 2050, exposure to potential earthquake risks in the cities of a developing country would be increased two-fold compared to present-day level according to the demographic-economic projection of urban population growth (Brecht et al. 2013). The interaction and amalgamation of existing

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vulnerabilities, element at risk, and potentially harmful natural processes have been attributed as the prime reason for such disasters (Birkmann 2006). Consequently, a better understanding of various interactive factors is sorely needed to effectively alleviate the risk of all types of disasters, including earthquakes. Such components include a) significant hazards and existing vulnerability components, and b) elements at risk within a community and over time (ADPC 2003; Carreño et al. 2007; UNISDR 2017; Aksha et al. 2019). The combination of hazard parameters and vulnerability indicators will thus allow the measurement of seismic risk even in the absence of reliable data for absolute loss assessment.

In general, existing vulnerabilities of the current population and properties can be associated with the potential risk of seismic activities. At present, approaches available for evaluating such vulnerabilities to different systems are widely distinguishable, wherein no specific method is applicable to all hazards (Calvi et al. 2006; Birkmann et al. 2013). Fundamentally, a vulnerability assessment is reliant upon the definition of perceived vulnerability itself from a practical and analytical point of view, as well as in consideration of end-user scientific assessment findings and vulnerable entities. Consequently, the importance of determining the most efficient and practical vulnerability assessment techniques based on the available data and technical resources is undeniable for risk reduction and management. Nowadays, the experiences of developing countries have resulted in an evolution of vulnerability conceptually in disaster discourses.

Typically, previous research efforts have addressed the issue of constructing seismic risk and vulnerability assessment methodologies or models in detail. The existing models in use are various, such as: 1) Earthquake Disaster Risk Index (EDRI) method: established to assess earthquake risk, which includes seismic hazard and vulnerability (Davidson 1997); 2) HAZUS: to estimate losses attributed to earthquake, such as physical, economic, and social elements (FEMA 2018); 3) Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters (RADIUS): enables users to perform an aggregated loss estimation in terms of building and population vulnerabilities (Okazaki 2000); 4) Methods for the Improvement of Vulnerability Assessment in Europe (MOVE) framework: conceptualizing the multi-dimensional nature of vulnerability and risk as a combination of exposure, susceptibility, and resilience components (Birkmann et al. 2013); 5) Integrated Earthquake Safety Index (IESI) and Relative Seismic Risk Index (RSRi): holistic methods of seismic risk assessment for urban fabrics that integrate earthquake hazard, vulnerability, and response capacity of the Tehran region (Hajibabaei et al. 2014; Mili et al. 2017); and others.

In brief, a literature review of the previous risk and vulnerabilities assessment model has underlined multiple excellent strengths; however, some limitations are also observed pertaining to its implementation across all circumstances and locations. In fact, utilisation of the methodologies requires appropriate and comprehensive data. An example of this data is building inventory stocks, including the structure and non-structure components, which are normally non-existent in most developing countries (Okazaki 2000; UNISDR 2016; Armaş et al. 2017; Mili et al. 2017). Besides,

most of the conventional models have been designed based on local conditions and experts, rendering their application largely confined to regions with similar parameters (Mili et al. 2017).

In the context of Malaysia, earthquake risk assessment is generally in its early stages still, faces various challenges (Indan et al. 2018; Tongkul 2021), and commonly focuses on the regions of Sabah and Pahang. Based on the historical records of earthquake activity, both areas have shown a concentrated distribution of such phenomenon (Lat and Ibrahim 2009; Alexander 2011a; Harith et al. 2017; Tongkul 2017; Sk Muiz et al. 2018). In recent years, however, numerous studies have been performed by local authorities and researchers towards establishing decreased seismic risks. Additional emphasis can be observed on the vulnerability assessment carried out in Sabah, which is located in the eastern part of the country (Ghafar et al. 2015; Tongkul 2015; Indan et al. 2018; Raduan et al. 2018; Roslee et al. 2018), whereas Pahang-based works are primarily seismic hazard-based in nature (Shuib 2009; Nabilah and Balendra 2012; Marto et al. 2013; Lam et al. 2016; Weijie Loi et al. 2018).

For example, Indan et al. (2018) have presented an Earthquake Vulnerability Assessment (EVA) geared towards recognizing social and environmental vulnerabilities, while the work of Roslee et al. (2018) and Aziera et al. (2021) are focussed on the physical and environmental vulnerability of the research area following the Ranau earthquake in Sabah. Here, building vulnerability-related studies are essential as the majority of buildings built in Malaysia have been designed with non-seismic resistance in mind (Adiyanto and Majid 2014). Therefore, addressing the problem of insufficient data for building vulnerability assessment has resulted in the use of Rapid Visual Screening (RVS) method to develop a building inventory. It is employed to map the physical vulnerability of the Kundasang area in Sabah (Ghafar et al. 2015). Accordingly, Raduan et al. (2018) have designed an earthquake threat map for the state by implementing the GIS application for the purpose of geographic location and attribute information classification and display in line with the threat level categories. Meanwhile, a recently-conducted study in Pahang is tasked with identifying the geographical variations of the social vulnerability index to seismic hazard. Thus, the scholars have focused on the aspects of social exposure related to the demographic data and distribution of residential building density accordingly (Sauti et al. 2020a; 2021). A study had exclusively proposed a method and a framework for seismic vulnerability assessment for the Malaysian setting (Sauti et al. 2020b).

Furthermore, a review of previous studies has indicated the critical need to develop a holistic approach in addressing effective measures aimed at reducing the risk of earthquakes in the Malaysian climate. In this particular context, much of the attention is directed to the thematic dimensions of vulnerability issues related to exposure, capacity, and resilience components in disaster management. Therefore, the lack of dedicated seismic vulnerability assessment methodologies for the country has driven the undertaking of the current study. This is further bolstered by activities such as several tremors recorded in Bukit Tinggi, Pahang between 2007 and 2010 and the Sabah earthquake in 2015, which have brought awareness regarding the possibility

that earthquake occurrences in Malaysia have gained traction over the past decade (Zainal et al. 2011; Adnan et al. 2015).

Seismic exposure is reviewed in the context of human and physical exposures (Cutter et al. 2003; Birkmann 2013; UNISDR 2016) to identify the most vulnerable groups across the population. Besides, an analysis of vulnerability variations either between or within a geographical range that may encounter similar hazard events is also offered (Birkmann et al. 2013). Accordingly, often-described characteristics of human and physical exposures influencing social vulnerability found in the literature include age structure, gender, disabled groups, household structure, and built environment (Morrow 1999; Cutter et al. 2003; Flanagan et al. 2011; Roncancio et al. 2020).

Alternatively, the aspect of resilience is generally associated with the capability held by a system or community to cope, absorb, adapt, anticipate, and recover effectively for the purposed of alleviating the impact of disasters (Birkmann et al. 2013; Atrachali et al. 2019). In particular, resilience indicators are correlated with the integration of economic resilience, significant communication facilities, and community resources (Buckle et al. 2000; Bergstrand et al. 2015). Therefore, the capacity literature in vulnerabilities is defined as the amalgamation of strengths, abilities, and resources available in a community to manage and handle the consequences of disasters, as well as to increase resilience (Hajibabae et al. 2014). In line with this, strengthening the tangible element at risk, including built structure, to withstand such consequences is considered a pivotal factor. Meanwhile, the physical coping capacity refers to the critical public facilities linked with public safety and security, such as healthcare services, police stations, and fire stations (ADPC. 2015; Banica et al. 2017; Mili et al. 2017). Accordingly, other identified built structures at risk in disasters are high-density occupancy structures and transportation networks (Rezaie and Panahi 2015).

Clearly, the term ‘seismic vulnerability’ applied in this study donates the outcome of a combination of factors (exposure, resilience, and capacity) that influences the potential loss or level of damage caused by a particular hazard. Meanwhile, ‘seismic risk’ refers to the interaction of seismic vulnerability with seismic hazards. ‘Seismic hazards’ reflect the possible physical phenomena (e.g. ground shaking, ground failures, etc.) associated with earthquakes that adversely affect people, society and the built environment.

This article aims to conduct a GIS-based seismic risk assessment at a local district situated in Pahang, Malaysia. This examines a holistic vulnerability model of exposure, resilience and capacity indicators to seismic hazard. The model serves as the fundamental criteria for risk assessment to identify the potential impacts of earthquake. To address this, we have attempted to solve a number of research questions on vulnerability and risk estimation. (i) What indicators represent the components of exposure, resilience and capacity, which can affect the level of seismic vulnerability of an area? (ii) Can the method prescribed by Iyengar and Sudarshan (unequal weighting schemes) possibly applied for calculating the weightage for selected indicators? (iii) How various vulnerability indicators are aggregated using a composite vulnerability index with seismic hazard to classify the seismic risk levels on a regional scale?

Table 1. Frequency of local earthquake events recorded in Peninsular Malaysia from 2007 to 2010. Source: (Alexander 2011a; Zainal et al. 2011).

Year	Location	Frequency	Magnitude
2007 – 2009	Bukit Tinggi, Pahang	24	1.7-3.5
2009	Kuala Pilah, Negeri Sembilan	4	2.6-3.2
2009	Jerantut, Pahang	1	3.2
2009	Manjung, Perak	1	2.8
2010	Kenyir Dam, Terengganu	1	2.6

Based on the outlined research questions, the main objectives of this study were set to estimate the seismic risk of Pahang, Malaysia by (i) proposing a seismic vulnerability assessment structure which composing of three essential indicators (exposure, resilience, and capacity) that were developed with their respective contributions represented by weighted values (ii) applying the GIS tools to generate the thematic maps of seismic vulnerability indices (exposure, resilience and capacity) and final seismic risk maps. It was previously shown that, most of the conventional models (seismic risk assessment) have been designed based on local conditions and experts which is not applicable for all areas as the multi-faced of vulnerability concepts. However, it can be modified by evaluating and applying necessary modifications in the indicators and their relevant weights (Mili et al. 2017). Thus, this study is investigating an integrated method to construct a composite vulnerability index based on an unequal weighting scheme. It is structured to fit the purpose for vulnerability assessments across district scale and local features. This approach is an alternative methodology for developed countries, which often face the lack of comprehensive and readily available data for vulnerability assessment. The weighting scheme method has been extensively used in several disciplines, particularly the field of climate change and has yet to be applied for calculating weights for seismic vulnerability and risk indicators.

2. Material and methods

2.1. Study area

In general, Malaysia is a country that possesses a relatively low seismic profile due to its geologically stable condition in the Indo-Sundaland region. As it is surrounded by the three major tectonic plates of Eurasian, Australian, and Philippine Plates (Marto et al. 2013), tremors can be felt continually due to frequent regional earthquakes (Adnan et al. 2005). Furthermore, the west and south coasts of the nation, otherwise known as Peninsular Malaysia, are somewhat influenced by these distant earthquakes. The source of impact is attributable to the most seismically active inter-plate boundary between the Indo-Australian and Eurasian Plates (Adiyanto and Majid 2014). Besides, Peninsular Malaysia has experienced local earthquakes since 1897, wherein more than 100 occurrences have been recorded (Adnan et al. 2015). The local earthquakes recorded in Peninsular Malaysia from 2007 to 2010 is statistically depicted in Table 1.

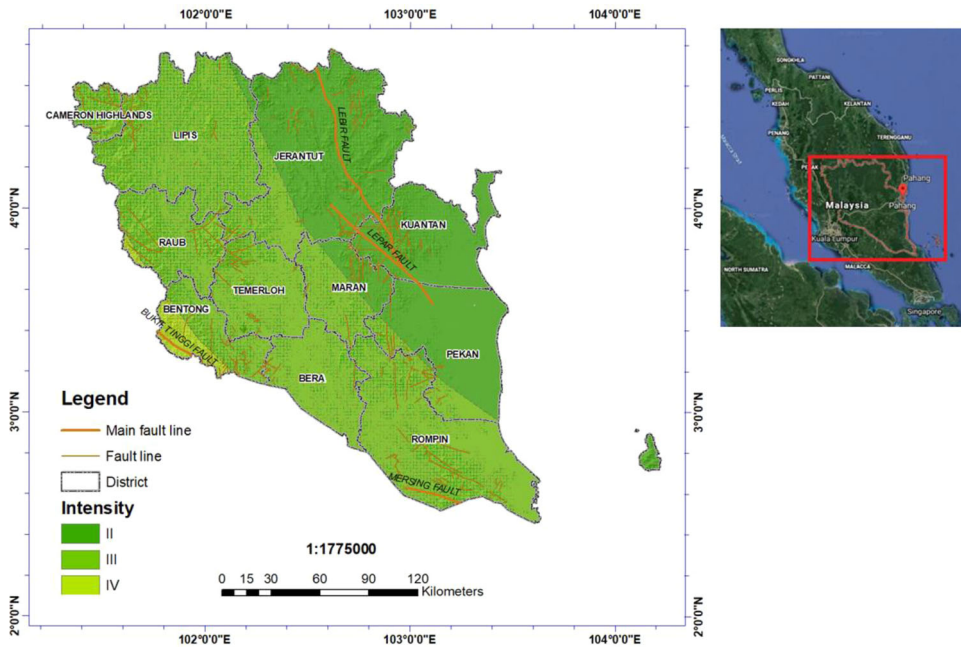


Figure 1. Seismic hazard zone (intensity map) and distribution of faults in Pahang (Source: Department of Mineral and Geoscience Malaysia (JMG), 2017).

Bukit Tinggi, Pahang has recorded the highest number of earthquake activities throughout time, whereby it encompasses the Bentong Fault Zone (i.e. referred to as the Bukit Tinggi Fault) and the Kuala Lumpur Fault (Marto et al. 2013). Due to their relatively near distance to Malaysian tourist and administrative centres, the position of these main active seismic faults has stimulated considerable interest and concern by the disaster management agencies and relevant authorities. Therefore, the state of Pahang, Malaysia, was deemed a good study area in performing empirical assessments on seismic vulnerability and risk based on the historical regional earthquake occurrences. The classification of seismic hazard zone (DSM 2017) and fault distribution in the region are comprehensively shown in Figure 1.

The seismic hazard map (intensity map) refers to the first edition map (2017) published and proposed by JMG, which has been employed as the standards for Peninsular Malaysia, Sabah, and Sarawak regions. It is valid throughout the amendment of Malaysia National Annex to Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings by the Department of Standards Malaysia (DSM). The map is underpinned as the guide and reference to all parties in developing areas that are at risk of earthquake disasters (PLANMALAYSIA 2018).

In brief, the central-west region of Pahang (i.e. Bentong district) could be identified as the most concerning zone (Zone IV) in line with the frequent reports of earthquake activities. Although a series of weak tremors has been felt around the area of Bukit Tinggi, their impact caused varying degrees of damages to infrastructures. This includes hairline cracks observed at a few houses in Janda Baik and Chemperoh

villages and considerable damage to Bukit Tinggi Secondary School and Bukit Tinggi police station (Lat and Ibrahim 2009). Therefore, the re-activation of Bukit Tinggi Fault with strike-slip movements have been thought to be attributable to the first wave of earthquakes recorded by a number of seismic stations in the area (Alexander 2011a). This underscores the critical need for constant monitoring by JMG and disaster response agencies in view of disaster preparedness and mitigation contingency plans.

An estimation of the extent of earthquake activities resulted in the suggestion for seismic vulnerability assessment of Pahang, Peninsular Malaysia, to factor in the identification of potential risk to the population and properties.

2.2. Seismic vulnerability assessment

The method implemented to assess the seismic vulnerability at the local district level integrated quantitative and qualitative techniques along with geospatial analysis via the GIS technology. The vulnerability assessment adhered to the standardized work initiated by Birkmann et al. (2013), which has been deployed by numerous research genres as it incorporates range of socio-economic and physical data for urban areas. Nonetheless, a slight modification was made to the MOVE framework (Birkmann et al. 2013) to suit the study context. After weighing in the basic indicators of social vulnerability index (Cutter et al. 2003) with several minor modifications, the definition of vulnerability given by UNISDR was integrated with, the three main vulnerability components of exposure, resilience, and capacity. Each component contained several sub-components. The selected indicators were identified and analysed for the study area based on the components. Adapted based on the existing model approach (Cutter et al. 2003; Birkmann et al. 2013), the process consisted of:

- a. Identification of vulnerability indicators and data collection
- b. Data normalization and weight determination of the selected vulnerability indicators
- c. Vulnerability index map preparation by using the GIS-based model, and
- d. Seismic risk map preparation

2.2.1. Identification of vulnerability indicators and data collection

Based on the systematic literature review, expert opinions, and data availability, the selection and structuring of three main indicators were thus completed, namely exposure, resilience, and capacity together with their respective indicator variables. The basic principles of the indicators selected in this study derived from various definitions and frameworks of vulnerability established and applied worldwide since the past decade (Davidson 1997; Bohle 2001; Pelling 2003; Birkmann et al. 2013). The growing literature pertaining to vulnerability has introduced a broad range of terms, including sensitivity, resilience, adaptation, adaptive capacity, risk, hazard, outreach, and adaptation policies. Turning to this study, the justification for selecting the vulnerability indicators is to define vulnerability within the context of multi-dimensional point of view, as listed in the following:

Table 2. List of data and sources (Source: Authors, 2020).

Module	Data Layer	Year	Format	Source
Hazard	Fault	2012	Line-vector	JMG
	Seismic zone	2016	Polygon- vector	JMG
Cadastral layer	Country	2010	Polygon-vector	MaCGDI
	District	2010	Polygon-vector	MaCGDI
	Road	2012	Line-vector	MaCGDI
	Administration Boundary	2012	Line-vector	MaCGDI
	Slope (DEM)	2012	Raster image	MaCGDI
Potential risk zones	Building	2011	Polygon-vector	MaCGDI
	Residential	2010	Polygon-vector	MaCGDI
	Public facilities (police station & fire station)	2012	Point & polygon -vector	MaCGDI
	School	2012	Point & polygon -vector	MaCGDI
	Healthcare service	2012	Point & polygon -vector	MaCGDI
	City	2012	Point-vector	MaCGDI
	Population / Census	2010	Polygon-vector	DOSM

- i. Exposure, is a crucial element of vulnerability risk that defines the extent of societies and properties under assessment in the geographical context of risk occurrence (Birkmann et al. 2013; UNISDR 2016). Measuring exposure demands an integrated understanding of components and how these factors can be amalgamated to contribute to the resilience of communities (Burton and Silva 2014; Carreno et al. 2016). These approaches include methods that use predominantly integral statistical data gathered from national census to assess the vulnerability of local populations.
- ii. Resilience indicators reflect the integration of a myriad adaptive capacities such as economic resilience, significant communication facilities, and community resources to responses and changes after adverse events (Cutter et al. 2010; Birkmann et al. 2013);
- iii. Capacity, which can be expressed in physical term, refers to the availability of the infrastructure required for effective adaptation in reducing disaster risk (ADPC. 2015; UNISDR 2018). Lack of resilience or coping capabilities in the society can be measured by the limitation of access and the mobilization of community or social-ecological capital to respond against predetermined hazards (Bergstrand et al. 2015; Welle and Birkmann 2015; Banica et al. 2017; Doorn 2017).

The selection and characterization of respective data were carried out and gathered from the agencies tasked with the responsibility for the purpose of vulnerability indicator identification and development at the municipal level. In this study, attribute data were derived from census data generated by Department of Statistics Malaysia (DOSM) (DOSM 2019) and spatial data obtained from JMG and Malaysian Centre for Geospatial Data Infrastructure (MaCGDI). Data from various federal government agencies were gathered and organized in accordance to the module application. Table 2 tabulates the details of the data and their resources.

Next, the functional relationship between identified indicators and vulnerabilities was distinguished by representing the indicators with positive or negative correlations. Based on previous studies or the theoretical assumptions detailed in Table 3, two types of practical relationships with increased vulnerability along with increasing

(i.e. decreasing) value of indicators can be interpreted. Comprehensive details on the selected variables for all indicators are included in Table 3, while the structures of seismic vulnerability index assessment are displayed in Figure 2. The seismic vulnerability assessment structure formulated in this study by incorporating the main indicators described earlier fits the purpose of vulnerability assessment across district scale and local features.

2.2.2. Data normalization and weight determination of the selected vulnerability indicators

The data source obtained in this study was in the multivariate form, resulting in the normalization process performed to standardize the dataset to a standard range (0 to 1) (UNDP 2018). This was carried out by using the linear min-max equation (Iyengar and Sudarshan 1982; Duong et al. 2016). Apart from the lack of standard ways of assigning weight to each indicator, the methods prescribed by Iyengar and Sudarshan (unequal weighting schemes) were deployed as the initial attempt to calculate the weighting values for the respective seismic vulnerability indicators in this study. The following mathematical equation is utilized when the indicator has a positive functional relationship with the vulnerability.

$$X^{ij} = \frac{(X^{ij} - \text{Min}x^{ij})}{(\text{Max}x^{ij} - \text{Min}x^{ij})}, (0 \leq x^{ij} \leq 1) \quad (1)$$

Contrarily, if a negative indicator functional relationship is seen with vulnerability, indicator normalization is done using the following formula:

$$X^{ij} = \frac{(\text{Max}x^{ij} - x^{ij})}{(\text{Max}x^{ij} - \text{Min}x^{ij})}, (0 \leq x^{ij} \leq 1) \quad (2)$$

where X^{ij} is the normalized value of the indicator i of the component j ; x_{ij} is the value of the indicator i ; and the $\text{Max}(x_{ij})$ and $\text{Min}(x_{ij})$ represent the maximum and minimum values of the indicators i of the component j , respectively. Then, the linear sum of x_{ij} is calculated using the following equation (3):

$$-yi = \sum_{j=1}^K w^j x^{ij} \quad (3)$$

M refers to region or district with the indicators of vulnerability (K). Therefore, normalized scores (x_{ij}) ($i=1, 2, \dots, M$; $j=1, 2, \dots, K$) and the weight (w_j) of each variable were computed; where ($0 < w < 1$) and $\sum_{i=1}^K w^j = 1$. The implementation of a weighted composite vulnerability index is recommended as certain variable factors cannot possibly provide the same impact on the assessment of the final vulnerability (Frigerio et al. 2016). Furthermore, the weight values for each variable should differ inversely as the variance between regions is the respective exposure measured. The following equations (4 and 5) are employed in determining the contribution or weight (w_j) for varying variables, where c represents the normalizing constant.

Table 3. Selection of variables with respect to indicators (Source: Authors, 2020).

Indicator/ Module	Variables dataset (unit)	Description / rationale	Functional relationship	References
Exposure	Percentage of age less than 15 years (%)	Children represent the most vulnerable group of the population as they lack life experience, capability, and tools during response activities in a disaster.	(+)	(Cutter et al. 2003; Flanagan et al. 2011; Martins et al. 2012; Frigerio et al. 2016; Bahadori et al. 2017; Aksha et al. 2019; Azzimonti et al. 2019)
	Percentage of age more than 65 years (%)	Most of the elderly population possess health and mobility difficulties or limitations, and require special need and care from others, especially in front of disasters.	(+)	(Cutter et al. 2003; Flanagan et al. 2011; Frigerio et al. 2016; Azzimonti et al. 2019)
	Percentage of female occupants (%)	Females' physical, social, and economic dimensions affect their ability to recover from disaster impact. Fewer resources and more barriers increase female vulnerability and risks.	(+)	(Morrow 1999; Cutter et al. 2003; Martins et al. 2012; Bahadori et al. 2017; Aksha et al. 2019; Sikandar and Khan 2019)
	Percentage of disabled occupants (%)	Individuals with disabilities usually encounter physical barriers or experience particular difficulties of communication that hinders them from effective reactions in disaster. Besides, interrelated factors such as social inclusion, inaccessibility to basic facilities and services (e.g. healthcare and education) and transportation systems have magnified the vulnerability level of this group.	(+)	(Rygel et al. 2006; Flanagan et al. 2011; Alexander 2011b; Ronoh et al. 2015)
	Density of population (per hectare)	Density of population is associated with disaster vulnerability and risk level. Disaster activities occurring in areas of high-density population tend to result in greater harm compared to less dense areas.	(+)	(Cutter et al. 2003; Flanagan et al. 2011; Rafiq and Blaschke 2012; Frigerio et al. 2016; Bahadori et al. 2017; Mili et al. 2017; Aksha et al. 2019; Azzimonti et al. 2019)
Resilience	Density of household (per hectare)	Both household density and household residence density contribute to the context of disaster risk and vulnerability. Variations of these factors may increase the impact of risk and vulnerability or vice versa. A region of higher density will result in more vulnerability due to higher exposure to disasters.	(+)	(Morrow 1999; Cutter et al. 2003; Aksha et al. 2019)
	Density of household residence (per hectare)	Earthquake disasters are correlated to building density, especially residential types. High-residential density indicates the increase of exposure level and a larger potential for damage to the element at risk.	(+)	(Alam et al. 2013; Rezaie and Panahi 2015; Armaş et al. 2017; Bahadori et al. 2017; Mili et al. 2017)
	Density of residential building (per hectare)	Telecommunication equipment and services are crucial during and in the aftermath of a disaster, especially to connect with response teams, support systems, and other family members. The higher number of households equipped with these facilities will enable them to communicate effectively and potentially decrease the resulting risk and vulnerability level.	(+)	(Doorn 2017; Aksha et al. 2019)
	Percentage owning telecommunication equipment and services (%)		(+)	

(continued)

Table 3. Continued.

Indicator/ Module	Variables dataset (unit)	Description / rationale	Functional relationship	References
Capacity	Percentage of gross income (%)	Low-income households suffer greater losses compared to high-income households due to limited opportunities to manage risk and strengthen their resilience. The relative relationship between gross household income and disaster impact is linear.	(–)	(Hajibabaei et al. 2014; Walker et al. 2014)
	Percentage of poverty incidence (%)	Poverty incidence is related to socio-economic inequality concerning the ability of a population to conserve resources sufficiently in risk-reducing measures, which include safety policy, savings, transportation facilities, and quality housing otherwise associated with disaster preparedness. Besides, heightened vulnerability levels among poor population groups are likely to be linked with higher mortality and morbidity rates.	(+)	(Morrow 1999; Rygel et al. 2006; Flanagan et al. 2011; Bergstrand et al. 2015; de Loyola Hummell et al. 2016)
	Gross Domestic Product (GDP) – agriculture (per capita)	GDP represents the indicator of economic resilience related to the regional ability to recover from disasters. Based on the economic structure, the agricultural sector is one of the largest contributors to Pahang's GDP and economic resources. In terms of disaster risk and vulnerability, the sector is associated with the capability to provide significant contributions to the state GDP growth, rendering it possible to face disaster effects accordingly. An example is the ability to mobilize funds and resources for the response and recovery phases.	(+)	(Hajibabaei et al. 2014; Noy and Yonson 2018; DOSM 2020)
	Percentage of population growth (%)	Accelerated population growth worldwide continues to increase the impact and magnitude of disasters. Densely-populated urban areas are typically correlated with the lack of quality housing, unequal distribution of wealth, imbalanced quality of life, and problems with immigration adaptation (i.e. cultural and linguistic barriers), thus increasing the level of risk and vulnerability to disasters.	(+)	(Cutter et al. 2003; de Loyola Hummell et al. 2016; Aksha et al. 2019)
	Public services: - Percentage of police stations (%) - Percentage of fire stations (%) - Percentage of healthcare services (%)	Public safety and security encompassing the services by the police station, fire station, and healthcare services are critical facilities that can be adversely impacted by a disaster. The total number of services subject to collapse or failure to operate can disrupt and multiply the negative impact of a disaster on the community-based risks.	(–)	(ADPC. 2015; Rezaie and Panahi 2015; Banica et al. 2017; Mili et al. 2017)
	- Percentage of schools (%)	Similarly, high-density occupancy structures such as schools would result in numerous deaths and injuries due to disaster consequences.	(–)	
	Density of road network (per hectare)	Roads are the main transport system for disaster mitigation and evacuation activities. A large number of transport networks may lead to an increased rate of evacuation processes and minimize injury and fatality prevalence.	(–)	(Buckle et al. 2000; Aliabadi et al. 2015; Rezaie and Panahi 2015; Mili et al. 2017)
			(+)	
			(–)	
			(–)	

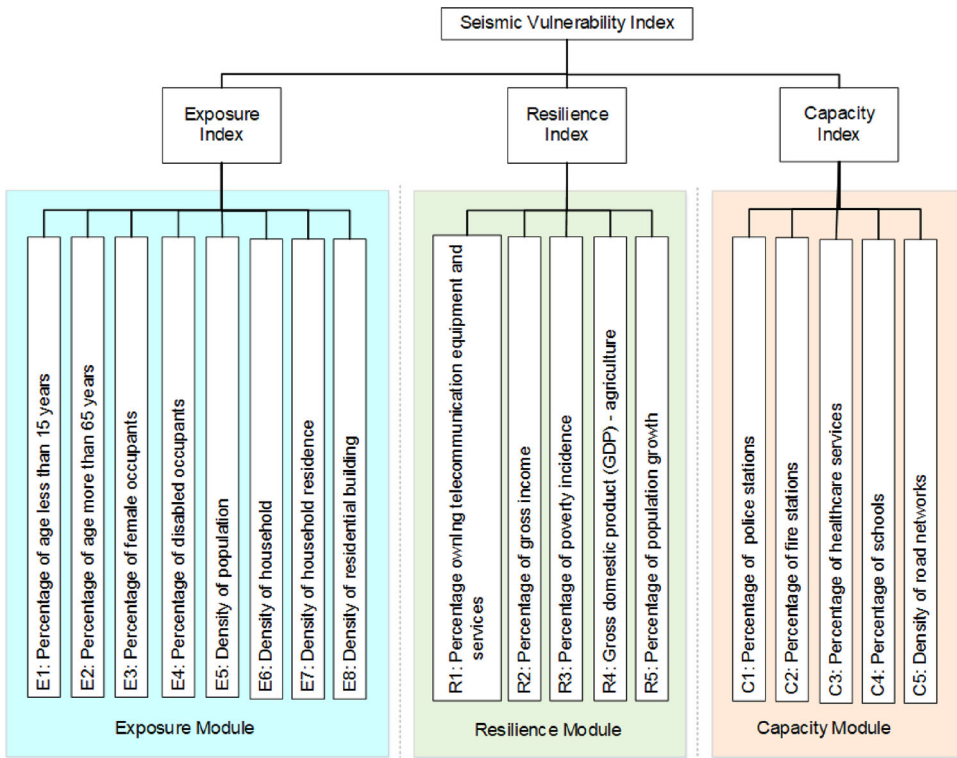


Figure 2. Structure of seismic vulnerability index assessment (Source: Authors, 2020).

$$w^j = c / \sqrt{\text{var}(x^{ij})} \quad (4)$$

$$c = \left[\sum_{i=1}^{j=K} 1 / \sqrt{\text{var}(x^{ij})} \right] - 1 \quad (5)$$

The statistical equation is geared to ensure that the remaining factors' contribution is not influenced by the significant differences of any variables and hampering the regional comparisons. The resulting weight values obtained for each variable are shown in [Table 4](#).

2.2.3. Vulnerability index map preparation by using GIS-based model

The most prevalent way of displaying the vulnerability level in a study region (i.e. including earthquake disasters) is by generating composite index maps (Davidson 1997; Beccari 2016). To this end, GIS tools are applied in performing spatial analysis and modelling to produce and map the vulnerability composite index accordingly (Tomaszewski 2015). In this study, each of the variable indicators was mapped to display the spatial data distribution by using the ArcGIS 10.3 software.

GIS modelling generally enables the simulation of possible vulnerability conditions and outcome scenarios based on the input variable dataset. Hence, the Model Builder function in ArcMap was employed to model the process of vulnerability index map

Table 4. Weight of vulnerability indicator variables (Source: Authors, 2020).

Variable indicator	Weight
Percentage of age less than 15 years	0.1341
Percentage of age more than 65 years	0.1390
Percentage of female occupants	0.1332
Percentage of disabled occupants	0.1295
Density of population	0.1271
Density of household	0.1231
Density of household residence	0.1224
Density of residential building	0.0916
Percentage owning telecommunication equipment and services	0.2089
Percentage of gross income	0.1094
Percentage of poverty incidence	0.1973
Gross Domestic Product (GDP) - agriculture	0.2344
Percentage of population growth	0.1690
Percentage of police stations	0.1595
Percentage of fire stations	0.1640
Percentage of healthcare services	0.2161
Percentage of schools	0.2392
Density of road networks	0.2213

development. In particular, the GIS-based model derived is equipped with the ability to tweak the variables within the model in evaluating various circumstances and simulating associations between different model variables or parameters (Tomaszewski 2015). Previous studies have shown that spatial modelling environments for earthquake disaster management are widely practised (Hassanzadeh et al. 2013; Van Westen 2013; Rezaie and Panahi 2015; Bahadori et al. 2017; Derakhshan et al. 2020). Thus, the GIS-based modelling methodology for this research is shown in Figure 3.

a. Thematic index map generation (exposure, resilience and capacity index map)

In the first phase of the GIS modelling process, the spatial layers were organized according to the vulnerability component or module. Geoprocessing tools (Polygon to Raster) were then employed to convert the vector layer to the raster layer dataset, thereby reclassifying the dataset to the group based on its values using the Reclassification tool. Based on the calculated weight and standard measurement scale, the raster layer dataset of each module was summed up together according to its significance using the Weighted Overlay function.

b. Vulnerability map generation

Then, the resulting thematic maps derived consisting of the exposure index map, resilience index map, and capacity index map were combined with the assigned equal weight (SCEMD 2002 as cited in Rafiq and Blaschke 2012) to generate and map the total vulnerability index map for the study area.

Next, the map generated from spatial modelling was classified based on the standard deviation or Z-values method to specify the standard deviation score distribution compared to the mean values (Cutter et al. 2003). Classification of equal value ranges for each category yields the proportion of standard deviation, which is achieved by using the following formula (6):

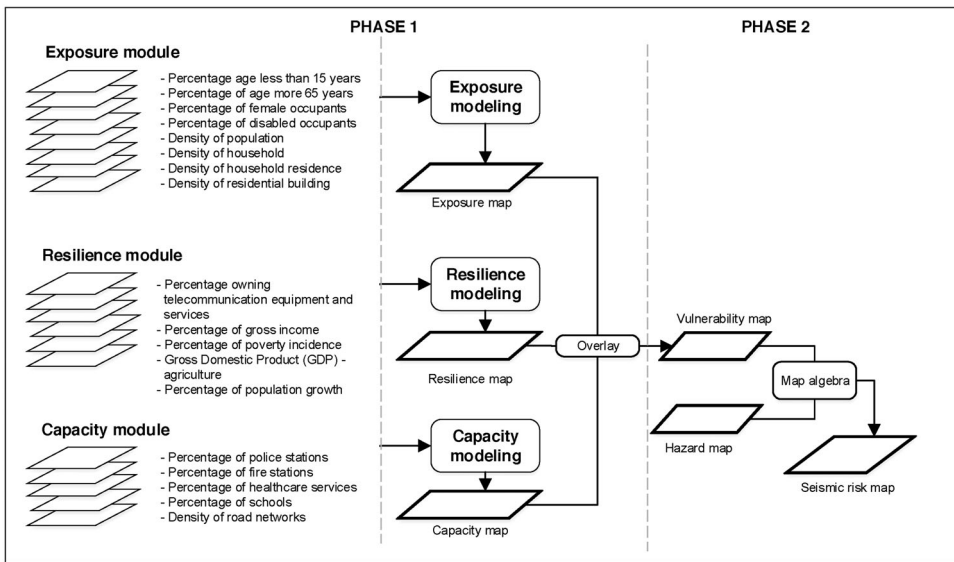


Figure 3. GIS-based methodology for seismic vulnerability and risk assessment (Source: Authors, 2020).

$$s = \sqrt{\frac{\sum (x^i - \bar{x})^2}{n}} \quad (6)$$

where x^i is the value of the data; $\bar{x}$ represents the mean of the data, and n is the number of data points. Typically, every standard deviation becomes a class at the intervals of one, one-half, one-third, or one-fourth standard deviations that differ from the mean values (Rygel et al. 2006; Frigerio et al. 2016; Aksha et al. 2019; Azzimonti et al. 2019). In other words, the statistical technique type of map would not reflect the actual values for the feature attributes; instead, it displayed the data distribution varied from the mean.

2.2.4. Seismic risk map preparation

In this phase, the derived map was overlaid with the seismic hazard map to develop the final seismic risk map for the Pahang state using the Weighted Overlay tool. The second phase, as depicted in Figure 3, shows the process of integrating the vulnerability index map and hazard map. The computation of geometric intersection for both maps involved the reclassification of each raster layer to a common scale and the assignment of equal weight. Besides, the Raster Calculator tool is applied to create and execute the following mathematical map algebra (7):

$$\text{Seismicriskmap} = \text{Vulnerability}^{\text{map}} \times \text{Hazard}^{\text{map}} \quad (7)$$

3. Results and discussion

The results generated from GIS-based modelling are thus discussed according to the respective phases of seismic vulnerability and seismic risk assessment as follows:

3.1. Vulnerability index map component generation

Figure 4 shows the output of quantitative thematic maps of the Pahang region, namely: exposure index map (a), resilience index map (b), and capacity index map (b). Meanwhile, the mean values and standard deviations calculated for the vulnerability component map are included in Table 5. Overall, Pahang displayed a relatively moderate and low exposure index with a small mean value (0.037) and standard deviation (Std Dev = 0.031). A majority of its districts demonstrated uniformity of exposure level as 91% or 10 out of 11 districts across the area scored less than + 0.5 Std Dev. In particular, Kuantan district was the only area that recorded 0.13 as the actual index value, which was more than + 1.5 Std Dev (9%). Geographically, Kuantan is Pahang's capital and largest city in the region. Therefore, this outcome was linked with the highest exposure index throughout the state, which was attributable to the highest percentage of children, elderly, and disabled occupants. Besides, the largest population density and residential building density recorded in the district further aggravated the higher level of exposure for the area.

Contrarily, the lowest exposure level was recorded in Cameron Highlands, Jerantut, and Rompin. In the case of Cameron Highlands, its high-density population density was offset by the minimal presence of vulnerable groups (i.e. children, elderly, female, and disabled occupants) that were likely to suffer from disaster (Buckle et al. 2000). In comparison, Jerantut was associated with a low exposure level due to small population density and low-density of residential buildings. Although it is known as the largest district in Pahang, 90% of land use in Jerantut is classified as forest reserves (JPBD 2015). In the context of Rompin, the district benefitted from the smaller number of elderly and disabled occupants, thus contributing to its low-level of exposure index.

In terms of the resilience level, the mean and value of resilience were 0.099 and 0.044, respectively. Here, Cameron Highlands displayed the lowest resilience index, thus indicating the highest level of vulnerability index in Pahang. The resilience index is composed of the economic district conditions, whereby the resident's gross incomes are high and the incidences of poverty are low. This was supported by the high rate of households equipped with telecommunication facilities, which potentially minimized the level of vulnerability and risk. Meanwhile, 27% of the area comprised of Bentong, Raub, and Kuantan districts were classified as low-level resilience or relatively high-level vulnerability as represented by their Std Dev ranging from -1.5 to -0.5 . Here, the key contributory factor to the resilience index is the indicators reflecting low rates of economic resources obtained from GDP (agriculture) in these districts, as well as Raub and Bentong having recorded lower rates of gross income compared to other districts. In contrast, the remaining 63% of the areas were considered as moderate to high in terms of resilience level, with Std Dev ranging between -0.5 and above. The rapid GDP growth underpinned the goal to reduce disaster vulnerability and risk by providing capital for response and recovery expenditure, which was an indicator fulfilled by the districts of Lipis, Rompin, Bera, and Jerantut.

In comparison with the exposure and resilience components, the distribution of capacity index throughout the region was 73% above the moderate level. Meanwhile, the remaining 27% yielded low or very low capacity index level, otherwise held by

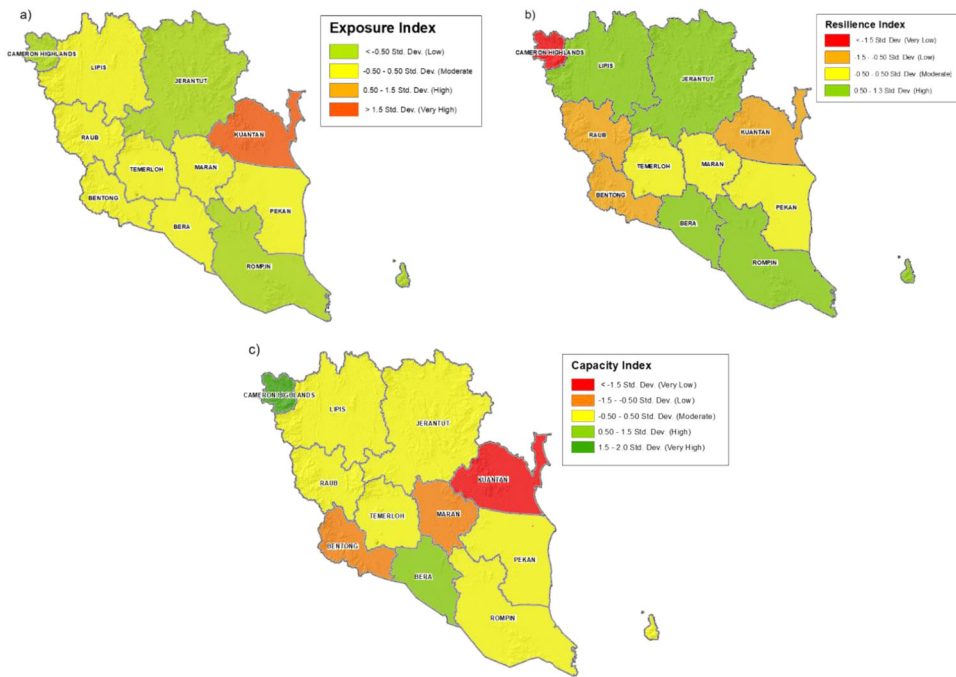


Figure 4. Thematic map of vulnerability components derived from the first phase of spatial analysis (Source: Authors, 2020).

the districts of Bentong, Maran, and Kuantan. Accordingly, the large number of facilities related to public safety and security that might be potentially exposed during a disaster could augment the vulnerability level of these districts, which was further exacerbated by the significantly greater index value for the number of schools. Contrary to the resilience level, Cameron Highlands recorded the highest capacity index level with its Std Dev value that was larger than + 1.5. Along with the low-level of exposure seen in the area, the hilly and mountainous topographical surfaces (Razali et al. 2018) have contributed to the low population density and residential density. Therefore, it resulted in the low number of safety and health services available, as well as low-density road networks; these elements collectively increased the level of vulnerability due to limited accessibility to the area.

Furthermore, the functional relationship of exposure index level was proportional to the vulnerability index (UNISDR 2016), thus indicating that Pahang's vulnerability level remained at moderate and low levels. Interestingly, the resilience index and capacity index correlations were non-linear with vulnerability, implicative of the theory that societies with low resilience and coping capacity would also be highly vulnerable (Vinchon et al. 2011; Birkmann et al. 2013; Hajibabae et al. 2014; Bergstrand et al. 2015; Azzimonti et al. 2019). The resilience and capacity index map output combined substantiated Pahang's vulnerability level index, which was relatively moderate to low.

Next, generating a total vulnerability composite index map was carried out by overlaying the derived maps accordingly, namely the exposure index map, resilience index map, and capacity index map. Figure 5 shows that the Kuantan district is located in the red zone due to recording the highest vulnerability index in the state.

Table 5. List of mean values and standard deviations for the vulnerability component map (Source: Authors, 2020).

Component	Mean value	Standard deviation
Exposure	0.037	0.031
Resilience	0.099	0.044
Capacity	0.100	0.024

However, it only represented 9% of the total overall district contributed by the two main factors of vulnerability, namely exposure and capacity in the area. In contrast, low capacity rates could be reflected in the high number of vulnerable groups and high-density residential buildings, as well as the high potential of health and safety facilities and road network affected. Similarly, the cumulative exposure, resilience, and capacity component of the Bentong district rendered it to be considered as the most vulnerable area. In view of this, over 45% of the northern and southern parts of Pahang were characterized with low to very low vulnerability level (i.e. green zone) due to low exposure potential and high resilience and capacity conditions. Conversely, 36% of the central area was classified as moderate to high-levels of vulnerability, otherwise referring to the districts of Pekan, Raub, Temerloh, and Maran. They were characterized with low resilience levels as represented by the indicators of low gross income, high poverty incidence, and high population growth.

In summary, the total vulnerability assessment results revealed that districts classified with relatively moderate to high vulnerability rankings corresponded to areas characterized with considerably moderate to high-level of exposure with losses caused by earthquakes. Such higher exposure could be attributed to the population density, residential building density, and larger number of occupants residing in the locality, which included children (age less than 15 years), elderly (more than 65 years old), female, and disabled occupants. Furthermore, the low levels of resilience in the central part of Pahang were due to the combination of the following factors: lowest gross income, high poverty incidence, and high rate of population growth. It should be noted that most of the districts with high-level vulnerability were influenced by their adaptive capacity level. This could be interpreted through the number of safety and health facilities available and limited access to road networks in areas that were affected by earthquakes, especially at the central part of the region.

3.2. Seismic risk map production

Figure 6 shows the output of potential seismic risk measurement, which is obtained by integrating the total vulnerability index map with the seismic hazard map. Here, the spatial distribution described the composite variables employed to assess the vulnerability level of a specific study area exposed to earthquake activities. Therefore, areas with high levels of vulnerability and hazard threat both might exhibit high levels of seismic risk, whereas the same logic would also hold true in contrary circumstances. Regardless, a transition could be observed from the low levels of seismic risk in the eastern areas, which could be attributed to the extremely high or moderate levels of seismic risk predominantly seen in the central-west region. Thus, the information

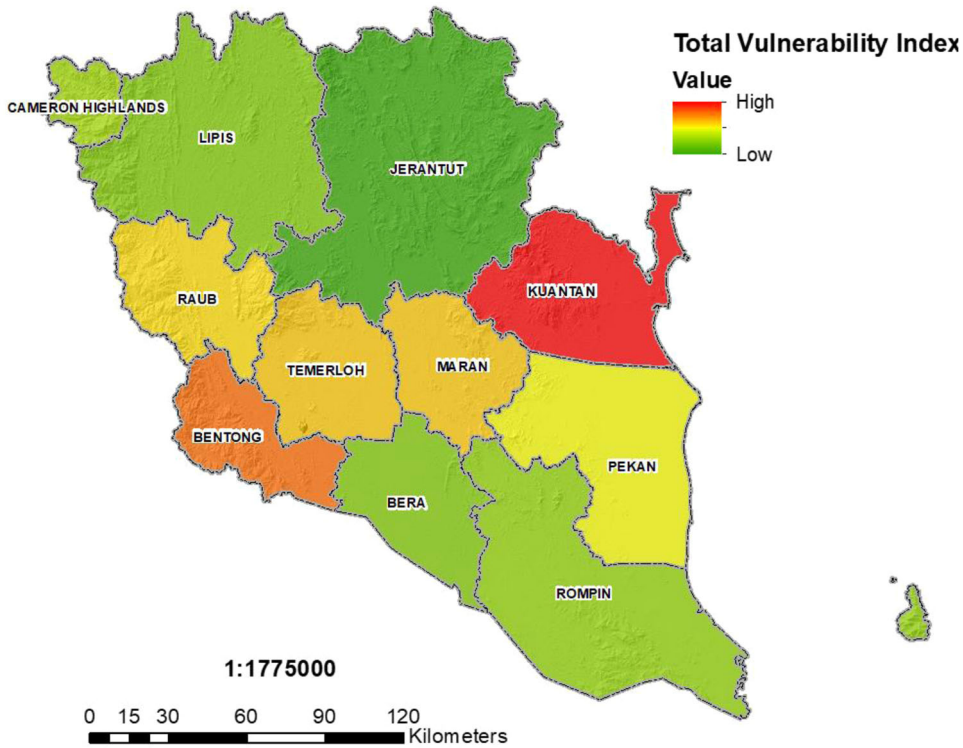


Figure 5. Total vulnerability map of Pahang (Source: Authors, 2020).

obtained from these maps is useful as an instrument to allow policymakers and relevant response teams in improving their risk reduction strategies.

Most of the eastern parts of Pahang were less seismically vulnerable as they were located in Zone II (green) and associated with a low possibility of earthquake occurrence, despite the moderate to high total vulnerability level for Pekan and Kuantan. In contrast, the most highly seismic risk area was observed at the central-west of the study area, which was denoted in red. A part of the Bentong district was particularly and highly vulnerable as its total vulnerability level was the maximum recorded, as well as the most active seismic activity zone observed. Moreover, the neighbourhood areas displayed a high degree of vulnerability as they were in Zone IV, whereby the earthquake magnitude ranged between 4.0 and 4.9.

As a majority (72%) of Pahang areas were located in Zone III (3.0 to 3.9 magnitude), this was reflected in the varying degrees of seismic risk ranging from low to high (Rompin, Bera, Lipis, Cameron Highlands, Raub, Temerloh, and parts of Jerantut and Maran). Despite the low probability of earthquakes occurring in Raub, Temerloh, and parts of Maran, certain high-level vulnerabilities contributed to making them 'high seismic risk'. Based on data availability and data adequacy for vulnerability assessment purposes, Bentong and the surrounding areas were significantly at high risk of seismic activities. This would prompt particular consideration by disaster management authorities in the context of long-term earthquake risk reduction and management strategies.

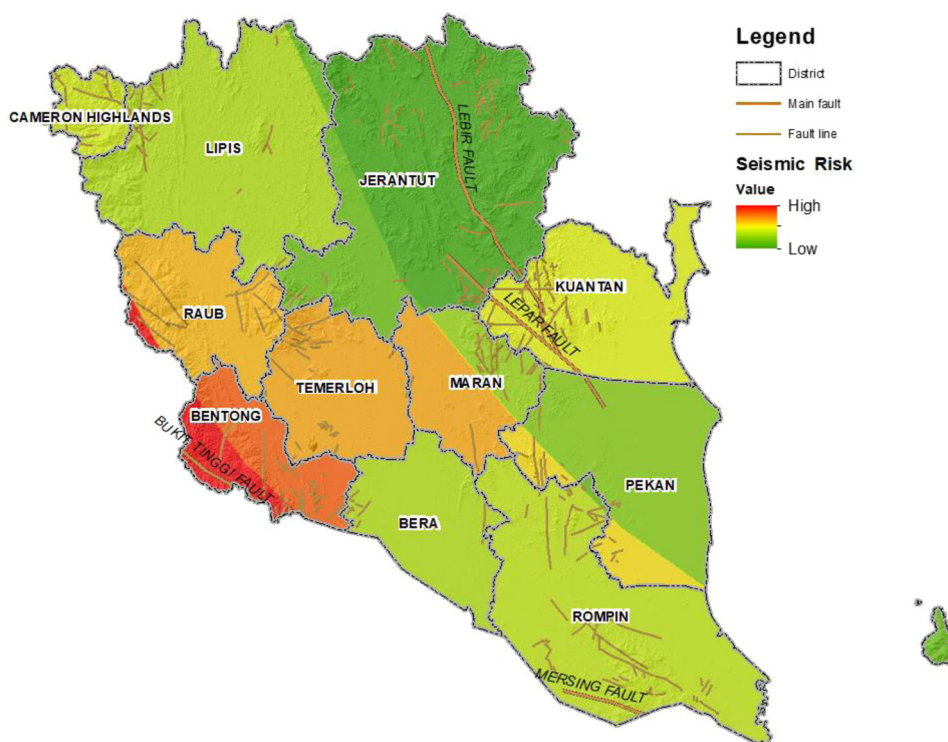


Figure 6. Seismic risk map of Pahang (Source: Authors, 2020).

4. Conclusion

This work represented the first attempt in assessing Pahang's seismic vulnerability and risk, allowing one to understand the spatial relationship between all possible vulnerabilities. They included exposure, resilience, and capacity elements and the element of earthquake hazard, which could be improved in many aspects. This article proposed a methodology for evaluating seismic vulnerability by developing a technique based on a holistic measure of socio-economic analysis conducted for the population of Pahang and its residential areas. The main findings provided a beneficial tool, which consisted of a significant selection of exposure, resilience, and capacity indicators; collectively, they required comprehensive understanding regarding the relationship among all influential factors in determining vulnerability at the regional scale. This was ascertained based on spatial modelling, namely by integrating the multivariate data analysis and GIS approaches in generating the overall vulnerability map and seismic risk map of the research area.

Furthermore, this study demonstrated the importance of combining total vulnerability map and seismic hazard map for the purpose of creating a new qualitative seismic risk map. Visualization of the derived map provided a valid basis for understanding the spatial heterogeneity of seismic vulnerability and risk possessed by Pahang, thus potentially implemented in the preliminary stages of regional risk planning and management strategies. In particular, the spatial pattern of seismic risk

showed that Bentong and its surrounding areas were the most populous at-risk area, whereby they were associated with a high number of inhabitants and residential density requiring particular attention from responsible agencies.

Accordingly, certain recommendations can be made for future studies in utilizing this methodology. They include the need to consider all uncertainties associated with the input data and estimate the spread of model errors through a sensitivity analysis. However, this requires the application of models to test areas known to experience earthquake events, which would allow measurement of their social vulnerability pre-disaster. Besides, it will yield a correlation with social disruption and damage to the building environment caused by earthquake disasters. Therefore, these elements can be tested in the Sabah region, which is the last area in Malaysia that have experienced a devastating earthquake previously on 5th June 2015. Validation tests were hampered previously due to constraints in terms of non-implementable statistical data from Census 2010 and the lack of comprehensive building inventory data. Despite the hurdles of data availability and lack of earthquake events experienced in the study area, verification on data validation, operational validation, and face validation (local experts) was performed with satisfactory outcomes.

Finally, an evaluation of seismic vulnerability and risk reveals the lack of ideal, identifiable, and empirical approaches that are optimal. However, a multitude of methods must be taken into account to realize this. Therefore, the set of indicators and methodologies proposed in this study could be adopted in the context of any region in Malaysia as it is suitable for replication in various scales, dynamics, and regional variations.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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